Dynamic torque and apical forces of ProFile .04 rotary instruments during preparation of curved canals

O. A. Peters & F. Barbakow

Department of Preventive Dentistry, Cariology and Periodontology, University of Zurich, Zurich, Switzerland

Abstract

Peters OA, Barbakow F. Dynamic torque and apical forces of ProFile .04 rotary instruments during preparation of curved canals. *International Endodontic Journal*, **35**, 379–389, 2002.

Aim To analyse torque and force generated whilst shaping curved canals using rotary instruments.

Methodology A specially designed computer-controlled testing platform was used to record events during the shaping of straight and curved canals in plastic blocks and in extracted human teeth using ProFile .04 instruments. Size 40 apical stops were prepared using crown-down, apical preparation and step-back procedures. Maximum torque, apically directed force and the numbers of revolutions were recorded at a resolution of 100 samples s^{-1}. Load causing separation as required by the ISO 3630–1 test and cyclic fatigue was also recorded. Mean maximum scores were calculated and statistically tested using one- and two-way analyses of variance.

Results Highest and lowest torque scores were recorded, respectively, in straight canals in plastic blocks at 25 Nmm and in natural canals at 14 Nmm. Significant differences were recorded for canal type and preparation phase ($P < 0.0001$). Loads causing separation varied from 3.7 to 32.3 Nmm. Apically directed forces ranged from 1 to 7.5 N. Again, there were significant differences depending on canal type and preparation phase ($P < 0.0001$). The number of revolutions during preparation ranged from 18 to 41. Size 15, 30 and 45 ProFile .04 instruments separated after 581, 430 and 402 revolutions, respectively, in a standard cyclic fatigue test.

Conclusions The new torque-testing platform details physical parameters during preparation of curved canals. To improve predictability, instrumentation sequences must be tested for excessively high torsional moments or forces. This study indicated that up to 10 curved canals could be safely prepared with a sequence of ProFile. 04 rotary instruments without separation due to cyclic fatigue. Efforts should continue to correlate root canal anatomy with torque and force generated during rotary root canal preparation.

Keywords: curved canals, cyclic fatigue, dynamic torque, force, Ni–Ti.

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Introduction

Chemo-mechanical preparation is an integral part of conservative root canal treatment (Weine 1996, Schäfer 2000). Much information has been documented during the past 30 years on the mechanical properties of ISO-normed hand instruments (Camps & Pertot 1994a, 1994b). However, during the last decade several new types of continuously rotating instruments were introduced. The evolution from hand- to engine-driven techniques was facilitated by manufacturing rotary instruments from nickel–titanium with its array of special properties (Serene *et al.* 1995, Thompson 2000). Initially, hand instruments were fabricated from nickel–titanium and their bending moments and degrees of deformation were tested (Camps & Pertot 1994c, Serene *et al.* 1995).

Simultaneously, studies documented that engine-driven rotary techniques including Lightspeed (Lightspeed Inc, San Antonio, TX, USA), ProFile .04 and .06

Correspondence: Dr Ove Peters, Department of Preventive Dentistry, Cariology and Periodontology, Division of Endodontology, University of Zurich, Plattenstr. 11, CH-8028 Zurich, Switzerland (fax: +41 1634 4308; e-mail: peters@zzmk.unizh.ch).

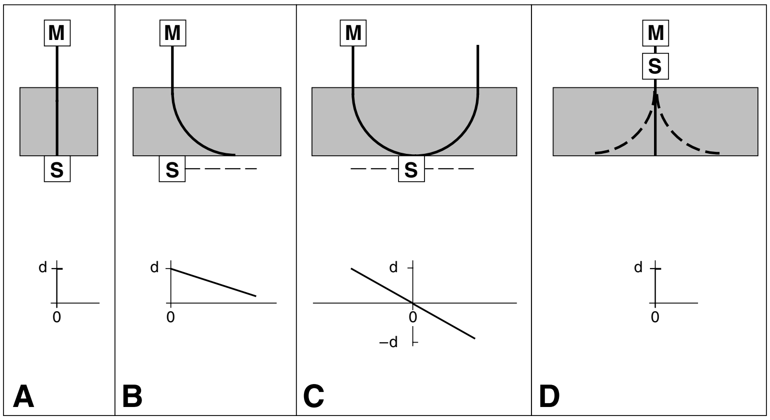

Figure 1 Schematic diagram showing different experimental set-ups and the relation between sensor (S) position and torque scores displayed as graphs below. Measurement in straight canals (A) can be executed correctly, whilst measurements in curved canals (B, C) lead to errors because sensors (dashed lines) are positioned differently. However, sensors positioned between motor (M) and rotating instrument yield exact scores in curved canals (D).

(Dentsply Maillefer, Ballaigues, Switzerland) and GT-Files (Dentsply Maillefer) produced better centred preparations without procedural errors such as apical zipping or elbows (Glosson *et al.* 1995, Portenier *et al.* 1998, Peters *et al.* 2001a). In addition, recent clinical research indicated that the outcome of endodontic therapy performed with nickel–titanium hand instruments was superior compared to teeth treated with stainless-steel counterparts (Pettiette *et al.* 2001).

Nickel–titanium files, particularly the engine-driven types, are prone to fractures. This has been discussed in laboratory studies (Zuolo & Walton 1995, Thompson & Dummer 1997a, Bryant *et al.* 1998a) and in a clinical survey (Barbakow & Lutz 1997). In that survey, 76% of the responding Lightspeed users reported at least one separated instrument after completing their one-day introductory courses. However, the underlying physical principles of rotary root canal instrumentation are not fully understood nor researched. Torque measurements are carried out using the guidelines set for the ISO 3630–1 test (International Organization for Standardization 1992), which cannot be extrapolated to rotary instrumentation. Likewise, there is no concise norm for cyclic fatigue tests.

Furthermore, the few documented studies on torsional moments and forces exerted during actual canal preparation were carried out using straight canals (Blum *et al.* 1999a, Sattapan *et al.* 2000a). The reason for this is apparently related to technical difficulties (Fig. 1). However, nickel–titanium instruments are particularly helpful for successful shaping of curved canals. Several studies using simulated canals in plastic blocks have repeatedly proved that canal anatomy influences the performance of instruments (Thompson & Dummer 1997a, 1997b, Bryant *et al.* 1998a, 1998b). This fact has recently been confirmed using canals in extracted human teeth (Peters *et al.* 2001a, 2001b).

To date, several torque-controlled low-speed motors have been introduced to help reduce the incidence of separation when using rotary instruments (TriAuto ZX, Morita, Dietzenbach, Switzerland; Endostepper, S.E.T., Germering, Germany; ART-Teknika, Dentsply Maillefer). The efficacy and clinical rationale for using these torque-controlled motors has been described recently in a case report (Gambarini 2000).

The efficacy of torque-controlled motors can be improved by relying on data collected during canal preparation. Therefore, the aim of the current study was to characterize physical parameters whilst shaping canals using a newly designed and specially constructed torque-testing platform. Torque, apically directed forces and the number of revolutions were determined for a sequence of ProFile .04 rotary instruments in both straight and curved simulated canals in plastic blocks and in curved canals in extracted human teeth. For comparison, selected ProFile instruments were also analysed according to ISO 3630–1 and other documented, established cyclic fatigue tests.

Materials and methods

General principles

Engine-driven rotary endodontic instruments can be tested in a number of ways including tests according to current ISO norms (i), cyclic fatigue tests (ii) or whilst preparing canals in plastic blocks and in extracted teeth (iii). Our newly developed torque-testing platform (Fig. 2) allows all three tests to be carried out because of the way the platform and its accessories are constructed. A main criterion of the device was to place the torque sensor between the endodontic instrument and the motor so that errors introduced by incongruent sensor axes and

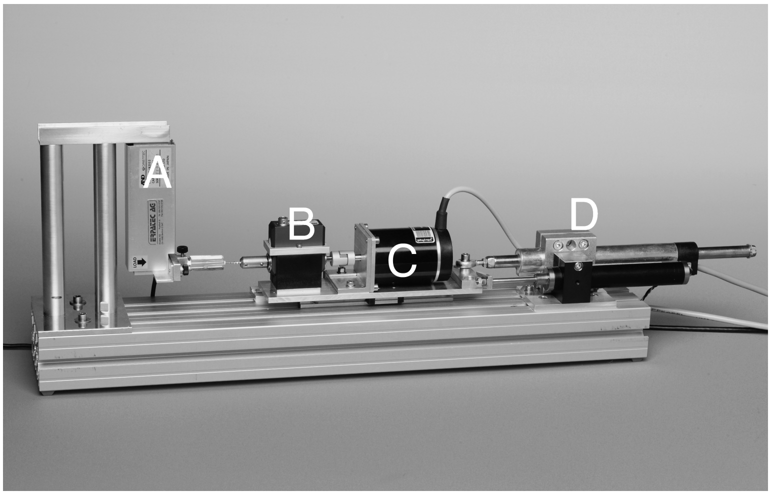

Figure 2 Major components of the torque-testing platform used during rotary preparation of curved canals: A, force transducer; B, torque sensor; C, motor; D, feed unit.

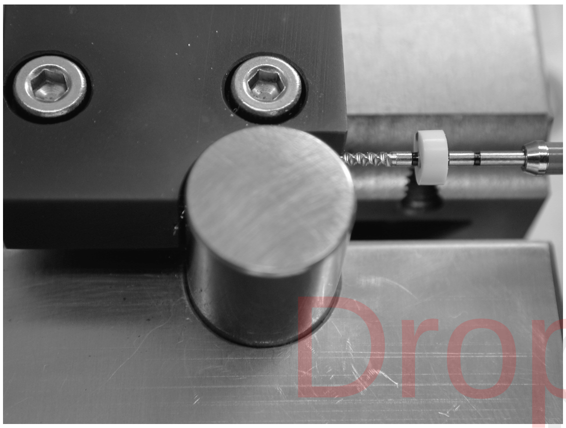

Figure 3 Tempered steel phantom to test cyclic fatigue fitted on the torque-testing device.

canal trajectories were avoided (Figs 1, 2). Variables which can be evaluated include torque on the instruments' shanks, apically directed force, instrumentation depth and the number of revolutions. These variables can be tested using either manual feed or programmed linear feed to exclude operator variability. Furthermore, additional modules such as tempered steel phantoms can be fitted to the device and enable cyclic fatigue and taper lock tests (Fig. 3).

Construction of the platform

Figure 2 details the components of the torque-testing platform. Extracted teeth or plastic blocks are mounted on SEM stubs (014001-T, Balzers Union AG, Balzers, Liechtenstein) and secured into a specimen holder attached to a strain gauge with preamplifier (A & D 30, Orientec, Tokyo, Japan). The holder was constructed to permit lateral movement so that the device can be aligned for varying positions of the canal orifices. The torque sensor (MTTRA 2, Microtest, Microtec Systems, Villingen, Germany) and the motor (Type ZSS, Phytron, Gröbenzell, Germany) are mounted on a stable metal plate, which can be moved along a low-friction guide rail for a width of 5 cm. A linear potentiometer (Lp-100, Midori, Osaka, Japan) is attached to the sliding platform to record linear movements.

These movements can be either executed manually or by a linear drive (P01-2380, LinMot, Zürich, Switzerland), which is, in turn, controlled by a computer program called 'ENDOTEST' which was specifically written for this purpose (Division of Endodontology, University of Zurich). The current version of this program was written in Pascal and runs on a Macintosh Power PC (Apple, Cupertino, CA, USA). Data for torque, force and insertion depth are acquired from the sensors using three analogue canals with a 12–bit interface (PCI-MIO-16XE, National Instruments, Austin, TX, USA). Real time collection of data is possible with sampling rates solely dependent on the amount of allocated RAM. For example, the storage need for a series of 10 measurements, recorded during 1 min using all three canals with a resolution of 100 measurements per s is approximately 1.44 mB. The sensors were regularly calibrated using precision-made levers and a set of brass weights of 1–400 g used according to the manufacturer's instructions. Variables recorded during each measurement were logged as Nmm or Ncm, N and in mm, respectively, for torque, force and distance of canal preparation and were stored for off-line analysis.

Parameters, which can be preselected in 'ENDOTEST', include (i) the number of analogue canals measured (1–3, torque, force and insertion depth) and (ii) the time allotted for the measurements at a resolution varying from 1 s^{-1} to 10 000 s^{-1}. All the measuring modes can be calibrated and amplified, within the range selected for each parameter (iii). The computer program also transmits the commands required to run rotary instruments at speeds varying from 1 r.p.m. to 2000 r.p.m. (iv). The linear feed can be programmed to execute complicated movements and up to 10 preselected movements can be stored in a pull-down menu (v).

Experiment a

A selected range of ProFile .04 instruments was tested to establish comparative scores for load at fracture and cyclic fatigue. ProFile instruments, sizes 20, 35 and 60 ($n = 8$, Batch nos 168046, 1702700 and 1670470, respectively) were tested according to the ISO 3630–1 test. A soft brass chuck was fitted into the specimen holder and the apical 3 mm of each instrument was held. Rotation was set at 2 r.p.m. and torque was recorded in relation to angular deflection with an accuracy of 0.5°.

ProFile instruments, sizes 15, 30 and 45 ($n = 12$, Batch nos 1604770, 1634800, 1634820, respectively) were tested to ascertain the number of rotations leading to separation in a tempered steel phantom with a 5-mm radius and a 90° angle (Haikel *et al.* 1999). All instruments in this study rotated at 250 r.p.m. Six instruments in each group were rotated without linear advancement until separation was recorded. The remaining six instruments in each group were programmed to have a linear feed and an oscillating movement of 2 mm at 0.5 Hz, mimicking the clinically used 'pecking' motion. The time to fracture was recorded using a stop watch and the numbers of rotations calculated to the nearest full number.

Experiment b

A sequence of ProFile .04 rotary instruments was used to prepare 10 plastic blocks with curved and 10 blocks with straight simulated canals (Ref. A 0177, Dentsply Maillefer). Working lengths in all canals were 18.5 mm and the curved canals had a 50° curvature with a 6.5-mm radius (Schneider 1971). All plastic blocks were then mounted on SEM stubs. Ten single-rooted mandibular incisors and canines selected from the Department's pool of extracted teeth were cleaned and also mounted on SEM stubs. The teeth, stored in 0.1% thymol, were decoronated so that their working lengths were similar to those of the plastic blocks. Digital radiographs (Digora, Soredex, Helsinki, Finland) were exposed initially and after the crown-down phase to determine curvature and final working lengths. Mean canal curvature of the extracted teeth was 13.2° ± 5.3.

Briefly, the preparation sequence included preflaring with a size 4 Gates-Glidden bur (Dentsply Maillefer) followed by a crown-down sequence using ProFile .04 instruments sizes 60–15 until working length was reached (Schrader *et al.* 1999). A size 40 apical stop was then prepared before completing with a step-back sequence using ProFiles sizes 45 and 60. Canals were copiously irrigated using tap water and syringe with a gauge 27 needle. All specimens were prepared by the same experienced operator (OP) using the manual linear feed of the torque-testing device.

Data analysis

Runs were recorded and stored in the proprietary format for subsequent off-line analysis. Then, original records were exported into a spreadsheet format (HIQ 2.2.1 for Macintosh, National Instruments). Maximum scores for torque and force were detected automatically. Numbers of rotations were counted under the condition that a minimum torque of 0.8 Nmm was present to exclude rotations occurring outside the canals. Variables were expressed as means (± SD) and compared using one- and two-way ANOVA's from a commercially available statistics package (StatView 4.02, Abacus Concepts, Berkeley, CA, USA). The level of significance was set at 95%.

Results

Regular calibration of the torque and force transducers before each series of measurements showed a linear and stable relationship between torque and force scores and the voltage (Fig. 4). The identical torque-measuring set-up was used for both the static and dynamic tests.

Experiment a

Load to failure was determined for sizes 20, 35 and 60 ProFile .04 instruments and findings for a size 60 instrument are shown as an example (Fig. 5). This example also details the deformation phases typical for nickel–titanium alloys. Means for torsional strain and rotational angle at failure are listed in Table 1. Torque values were significantly different between the file sizes investigated ($P < 0.0001$), whilst the angles were not.

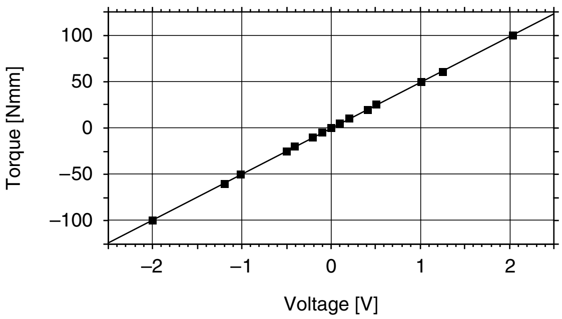

Figure 4 Example of a calibration graph indicating a linear relationship between torque (M) and voltage (U) with $M = -0.026 + 4.926\ U$.

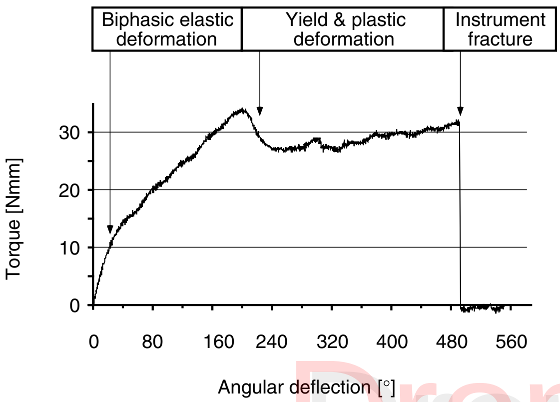

Figure 5 Line diagram of a 'load to fracture' run of a size 60 ProFile .04 performed according to the ISO 3630–1 test, indicating biphasic elastic deformation, yield and plastic deformation characteristics of nickel–titanium alloy.

Table 1 Load to fracture and angular deflection for selected ProFile .04 rotary instruments carried out according to the ISO 3630–1 test ($n = 8$)

Instrument	Torque [Nmm][a]	Angle [°][b]
ProFile 20.04	3.66 ± 0.51	590.1 ± 50.4
ProFile 35.04	13.80 ± 1.24	614.1 ± 93.4
ProFile 60.04	32.30 ± 2.91	514.3 ± 131.2

[a]Significantly different torque scores (ANOVA, $P < 0.0001$).
[b]No significant differences in rotational angles.

Results of the cyclic fatigue tests for size 15, 30 and 45 ProFile instruments, expressed as numbers of rotations to failure, are listed in Table 2. In general, fatal cyclic fatigue occurred at 400 rotations or greater. Significantly higher scores were recorded for the size 15 instruments, whilst ProFile sizes 30 and 45 had similar scores. The only significant difference noted between the static and the oscillating movements of the instruments, mimicking the clinically used pecking motion, was that recorded for the size 15 ProFile instrument ($P < 0.01$, Table 2) which fractured after 798 ± 194 and 581 ± 74 cycles with and without oscillations, respectively.

Table 2 Number of rotations to failure in a cyclic fatigue test carried out using a stainless steel phantom with 90° and 5 mm radius

Instrument	A Static	B Oscillating
ProFile 15.04	581 ± 74[a]	798 ± 194[b,a]
ProFile 30.04	430 ± 94	438 ± 51
ProFile 45.04	402 ± 78	392 ± 79

A, static instrument position; B, oscillating movement with 0.5 Hz and 2 mm width.
[a]Significantly different to sizes 30.04 and 45.04 ($P < 0.01$).
[b]Significantly different to size 15.04 in test A ($P < 0.01$).

Experiment b

A total of 356 preparation cycles in plastic blocks or extracted teeth were analysed. Torque values during simulated canal preparation differed widely with respect to canal types and instrument sizes and mean maximum scores are listed in Figure 6. Two significantly different ($P < 0.01$) groups of instruments were identified by virtue of their torque scores. First, the smaller ProFile instruments, sizes 20–30, in which torque values did not exceed 6 Nmm whilst secondly, the larger instruments, sizes 35–60, generated mean torque scores of up to 25 Nmm. Furthermore, within each instrument size, the highest torque scores were recorded in plastic blocks with straight simulated canals, whilst canals in natural teeth had the lowest torque scores. In most of the larger instrument sizes, this difference was statistically significant (Fig. 6).

Comparing the three preparation stages, size 60–20 instruments used in the crown-down phase generated maximum mean torques from 22 to 4 Nmm. In contrast, during apical preparation to a size 40, torque scores of 30 Nmm and greater developed. Similarly high torque scores were also recorded during the step-back phase. A two-way ANOVA indicated a highly significant effect of both canal type and instrumentation phase ($P < 0.0001$) on the torques generated, whilst a combination of both factors had no effect ($P > 0.05$, Table 3).

Similarly, the results of the apically directed forces were also grouped by instrument size and canal type (Fig. 7). In extracted teeth, the mean forces generated ranged from 3.5 and 5.5 N, but did not differ significantly

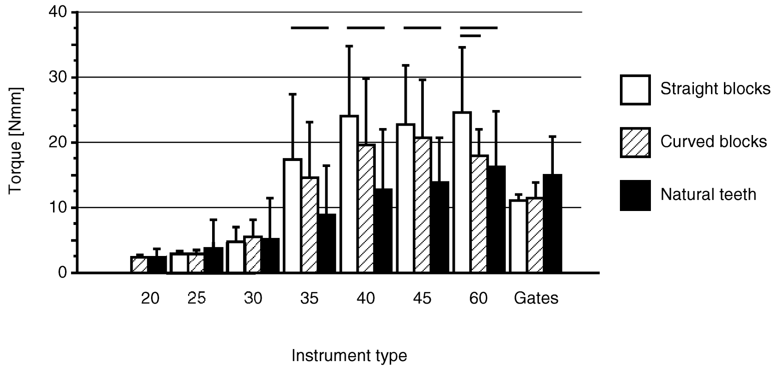

Figure 6 Bar diagrams detailing torque scores generated whilst preparing various canal types using ProFile .04 rotary instruments. Significant differences within one instrument size are indicated by horizontal bars ($P < 0.05$ or 0.01).

Table 3 Two-way analyses of variance carried out separately for torque, force and rotations during simulated rotary root canal preparation ($n = 356$)

Variable[a]	Factor[b]	DF	F-Value	*P*-Value	Post-hoc significance
Torque	Prep. stage	2	46.248	<0.0001	All
	Canal type	2	14.610	<0.0001	All
	Phase × canal	4	0.744	=0.562	–
Force	Prep. stage	2	54.408	<0.0001	All exc. AP versus SB
	Canal type	2	12.626	<0.0001	All exc. teeth versus curved blocks
	Phase × canal	4	18.321	<0.0001	–
Rotations	Prep. stage	2	7.935	=0.0004	All exc. AP versus CD
	Canal type	2	28.148	<0.0001	All
	Phase × canal	4	6.175	<0.0001	–

[a]Dependent variables torque, force and number of rotations.
[b]Independent factors. Preparation stage: Crown-down (CD); apical preparation (AP); step-back (SB) and canal type: straight plastic blocks, curved plastic blocks and natural teeth.

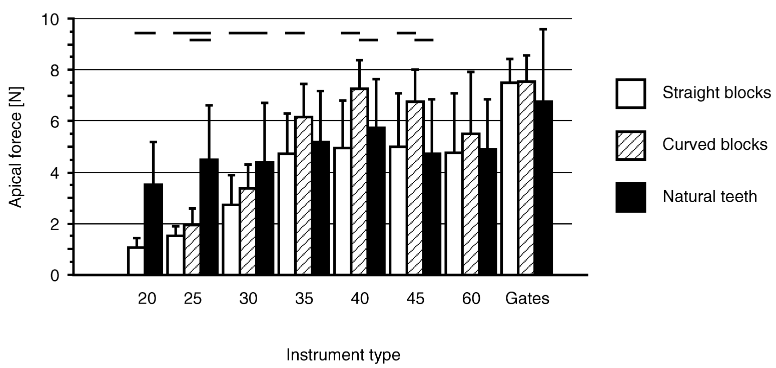

Figure 7 Bar diagrams detailing apical forces exerted whilst preparing various canal types using ProFile .04 rotary instruments. Significant differences within one instrument size are indicated by horizontal bars ($P < 0.05$ or 0.01).

between instruments. In contrast, for plastic blocks, forces decreased with decreasing instrument size. Generally, forces were high for curved canals in plastic blocks (maximum 7.3 N for ProFile no. 40) and low for straight canals in plastic blocks (4.9 N for ProFile no. 40).

When grouped into preparation phases, sizes 35 and 40 were used with significantly higher forces during crown-down (6 N and 7.5 N, respectively) than during the apical preparation (3.5 N and 6 N, respectively). These results were statistically significant ($P < 0.01$ and $P < 0.05$, respectively). A two-way ANOVA indicated that the apically directed forces were significantly affected by both canal type and preparation stage ($P < 0.0001$), as well as by a combined effect ($P < 0.0001$, Table 3).

The number of working rotations during preparation was determined accepting a torque threshold of

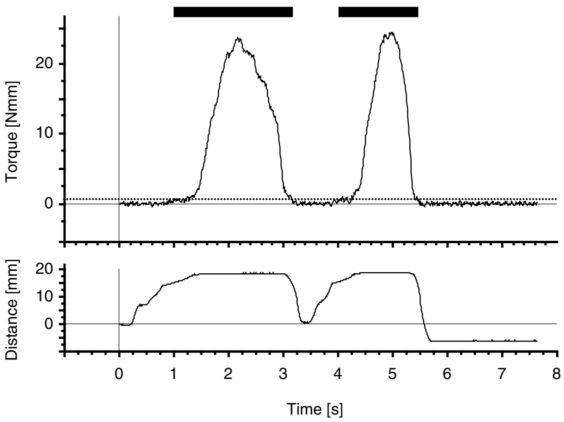

Figure 8 Line diagram of a typical recording during apical preparation of a curved canal in a plastic block using a size 40 ProFile .04 instrument. The number of revolutions counting from the entrance of the canal totalled 22, whilst only 13 revolutions generated torque (black bars) above the minimum torque threshold (0.8 Nmm, marked by dotted line).

0.8 Nmm (Fig. 8). Repeatedly, the instruments' working times determined in this way made up only 50% of the total preparation times (Fig. 8). The mean number of revolutions required to complete the crown-down, apical preparation and step-back phases of canal preparation varied from 41.3 (size 40 in curved canals in plastic blocks) to 18.3 rotations (size 25 in straight canals in plastic blocks). Grouped by instrument size, the numbers of rotations were generally highest in curved canals in plastic blocks whilst canals in natural teeth yielded the lowest scores (Fig. 9). A two-way ANOVA indicated highly significant effects of canal type and preparation phases, as well as a combined effect on numbers of working rotations ($P < 0.001$, Table 3).

Figures 6, 7 and 9 detail the scores for the size 4 Gates-Glidden burs recorded for torque, force and number of rotations, respectively. Similar scores were found for torque and number of rotations with Gates-Glidden burs compared to those recorded for the size 60 ProFile instruments, except that a higher force directed apically was recorded for Gates-Glidden burs.

Discussion

Amongst several factors, success or failure of endodontic therapy depends on the quality of canal preparation (Pettiette *et al.* 2001). Canals can readily be prepared *in vitro* with nickel–titanium rotary instruments such as ProFile .04 to have smooth and continuously tapering walls (Bryant *et al.* 1998a, 1998b). These preparations also minimize procedural errors such as apical zipping or ledging and improve obturation and thereby reduce apical leakage (Wu *et al.* 2000). Moreover, rotary instruments allow larger apical preparations (Schrader *et al.* 1999) with little or no canal transportation (Portenier *et al.* 1998). However, the increased risk of separation of nickel–titanium instruments remains a significant problem for many clinicians. Although some authors reported a high number of instruments showing plastic deformation after use with few separations (Thompson & Dummer 1997a, 1997b), others documented a higher incidence of fractures (Zuolo & Walton 1995, Mandel *et al.* 1999).

Previous studies described findings related to bending moments and torsional properties (Serene *et al.* 1995) as well as the cutting efficacy (Schäfer & Lau 1999) of nickel–titanium hand instruments. However, it is more difficult to study these properties correctly whilst preparing canals with rotary instruments. Technically, torque is measured in relation to a rotational axis, which should coincide with the instrument's long axis (Fig. 1). Consequently, a resulting torsional moment can be measured whilst the instrument rotates in a straight canal. This

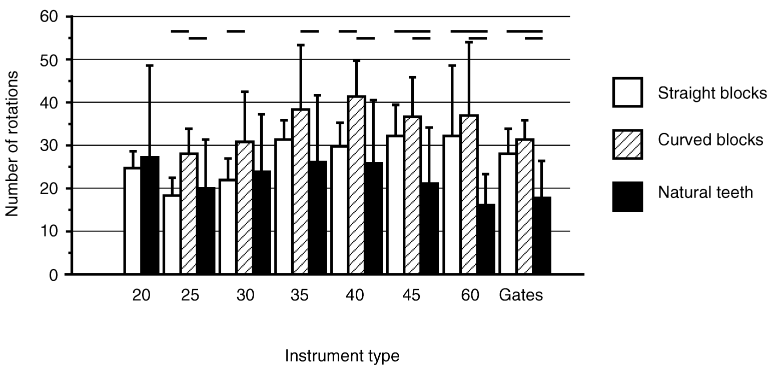

Figure 9 Bar diagrams detailing the number of revolutions counted whilst preparing various canal types with ProFile .04 rotary instruments. Significant differences within one instrument size are indicated by horizontal bars ($P < 0.05$ or 0.01).

Table 4 Literature review of torque scores assessed with different measuring set-ups

Instrument	Method	Torque	Reference	Recalculated[a]
K-File norm values #15–45	ISO 3630–1 Load to failure	8–120 gcm	ISO 1992	0.8–12 Nmm
K-File, Ni–Ti #15–55	ISO 3630–1 Load to failure	16.2–266.6 gcm	Rowan *et al.* (1996)	1.6–26.7 Nmm
ProFile Series 29, #2–5 (øD1 13–48)	ISO 3630–1 Load to failure	30.7–254.1 gcm	Silvaggio & Hicks (1997)	3.1–25.4 Nmm
Quantec #2–10	Strain gauge, Load to failure	23.0–200.2 gcm	Sattapan *et al.* (2000a)	2.3–20 Nmm
ProFile .04 #20–60	ISO 3630–1 Load to failure	3.7–32.3 Nmm	This paper	3.7–32.3 Nmm
ProFile .04 & .06 #20–35	'Endographe' straight canals	$7–20 \times 10^{-5}$ Nm	Blum *et al.* (1999a)	0.07–0.2 Nmm
ProFile .04 & .06 #15–35	'Endographe' straight canals	$4–30 \times 10^{-5}$ Nm	Blum *et al.* (1999b)	0.04–0.3 Nmm
Quantec #2–10	Strain gauge straight canals	1.2–284.4 gcm	Sattapan *et al.* (2000a)	0.12–28.4 Nmm
ProFile .04 #20–60	Torque platform various canals	1–25 Nmm	This paper	1–25 Nmm

Results listed above the shaded line detail load to fracture according to the ISO 3630–1 test, whilst results below the shaded line detail torques generated during canal preparation.
[a]Recalculated into SI units: 1 gcm ~0.1 Nmm (1 Nmm = 1 mNm).

principle was recently utilized in experiments by Blum *et al.* (1999a) and Sattapan *et al.* (2000a). Unfortunately, the results of these tests do not hold for curved canals, whilst nickel–titanium rotary instruments were primarily developed to shape curved canals. Furthermore, the incidence of instrument separation, clinically, is probably higher in severely curved than in straight canals.

It was decided to design and construct a platform to allow torque and force measurements in curved canals (Figs 1, 2). Using sensors with high resolution and regular calibration procedures, the amounts of torque that the motor transferred to the instrument's shank could be recorded, in real time, during canal preparation. The amount of torque generated clearly depends on the size of the contact areas between the instruments and the canal walls, as was recently demonstrated (Blum *et al.* 1999b). Clinically, however, the size of the contact area is unknown and it can vary following various instrumentation sequences.

Torsional load to separation as described by the ISO 3630–1 test was also recorded using the torque-testing device. The selected ProFile .04 instruments separated at torque scores varying from 3.7 Nmm to 32 Nmm. These results are in accordance with those stipulated by the ISO norm and with other documented findings (Table 4, Silvaggio & Hicks 1997). Furthermore, when torsional strain was plotted against deflection angles, curves typical for nickel–titanium (Rowan *et al.* 1996, Thompson 2000) were constructed (Fig. 5).

In contrast to these standard measurements, there were significantly higher torsional moments for most ProFile .04 rotary instruments tested during the simulated canal preparations. Interestingly, the highest torsional moments were generated in straight canals in plastic blocks, whilst the lowest scores were recorded in canals in extracted teeth (25 Nmm vs. 14 Nmm). This again emphasizes the importance of size of contact areas and the differences in surface texture between plastic blocks and extracted teeth. In addition, rather high torques were recorded during apical preparation in curved canals in plastic blocks using size 35 and 40 ProFile instruments. This finding might explain the high incidence of instrument deformation and fracture in laboratory studies (Thompson & Dummer 1997b) and during continuing education courses.

Table 4 lists previously reported torque scores found either according to the ISO 3630–1 test or during canal preparation. Differences in the scores between the present paper and those reported by Blum *et al.* (1999a, 1999b) may be due to varying instrumentation sequences and larger apical preparations in the current study. Moreover, the 'endographe' used by Blum *et al.* (1999a, 1999b) was developed to assess forces developed during hand instrumentation (Blum *et al.* 1997). The

'endographe' is similar to another device (Sattapan *et al.* 2000a), both of which use conventional dental handpieces. This is not the case in the currently described torque-testing device.

Some confusion occurs when using the unit 'gcm' to describe torque. Because both 'gcm' and 'Nm' have been used, scores were recalculated to compare findings reported in the literature and summarized in Table 4. Sattapan *et al.* (2000a) described torsional moments for Quantec instruments that were similar to the current results. It is evident from Table 4 that very low scores (<0.3 Nmm) have also been found (Blum *et al.* 1999a, 1999b).

In the current study, apically directed loads of up to 7.5 N were recorded for all larger instruments. Lower scores were found in straight canals in plastic blocks compared to the scores recorded in canals in extracted teeth. Irrespective of the type of rotary instrument, all manufacturers recommend using only light pressure. Unfortunately, the word 'light' is not numerically defined. This is reflected when forces as low as 0.1 N were demonstrated for size 2 Quantec 2000 instruments (Sattapan *et al.* 2000a). In contrast, the current study confirms earlier findings for apically directed forces (Blum *et al.* 1999a). However, it is important to note that despite relatively high apical forces in the present study, no ProFile instruments separated during canal preparation.

A recent retrospective analysis of separated instruments indicated two main modes of failure, namely, torsional and flexural types (Sattapan *et al.* 2000b). Flexural fractures may arise from minute surface defects within the instruments (Eggert *et al.* 1999, Luebke *et al.* 2001) and occur after cyclic fatigue. This effect has been extensively tested utilizing various experimental conditions (Pruett *et al.* 1997, Haikel *et al.* 1999, Yared *et al.* 1999, 2000). In order to compare cyclic fatigue, reported as number of revolutions to failure, a tempered steel phantom similar to that recently described (Haikel *et al.* 1999) was incorporated in the torque-testing device. The results reported in the current study for this criteria for some selected ProFile.04 instruments agree with recent findings reported for these instruments (Haikel *et al.* 1999, Yared *et al.* 2000). In addition to the static standard cyclic fatigue test, an oscillating 'pecking' motion was also carried out using a second group of ProFile .04 instruments. Unexpectedly, the pecking motion did not significantly enhance the lifespan of size 30 and 45 ProFile instruments. When compared to the number of revolutions actually occurring during canal preparation, a safety factor indicates that at least 5–10 curved canals can be prepared with a set of ProFile .04 instruments. Original data recorded during the current study showed that any instrument generated torque for roughly 50% of the time it rotated. In other words, it is unlikely that cyclic fatigue can occur if a rotating instrument does not significantly contact canal walls. Consequently, cyclic fatigue is not necessarily the main reason for instrument failure.

Interestingly, significant differences were found between the three types of canals used in the current study. Although canals in plastic blocks presented highly standardized *in vitro* conditions, their canal cross-sections and surface properties differ from that of canals in extracted teeth. Moreover, the effect of the complicated three-dimensional anatomy on canal preparation must also be considered (Peters *et al.* 2001a, 2001b). Likewise, operator experience resulting in a wide range of apical forces may also be a factor (Mandel *et al.* 1999).

To summarize, the current study is the first to report torsional moments during rotary preparation of curved root canals. Further experiments with automated feed are required to detail the effects of instrument design or sequence on torsional moments and apically directed forces. In the future, the torque-testing device described in this paper should be combined with three-dimensional analysis to study the relationship between root canal anatomy and physical parameters during rotary preparation.

Conclusions

1 Torsional moments can be evaluated during simulated preparation of curved root canals using the torque-testing device described in this paper.

2 A specific sequence for ProFile .04 rotary instruments intended to produce large apical stops generated torque scores greater than 20 Nmm for size 35 and 40 instruments. Apically directed forces exceeded 1.5 N in all cases, but were less than 8 N.

3 During simulated canal preparation, the number of revolutions did not exceed 41, indicating that up to 10 curved root canals can be safely prepared with a set of ProFile .04 rotary instruments.

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References

Barbakow F, Lutz F (1997) The 'Lightspeed' preparation technique evaluated by Swiss clinicians after attending continuing education courses. *International Endodontic Journal* **30**, 46–50.

Blum JY, Machtou P, Esber S, Micallef JP (1997) Analysis of forces developed during root canal preparation with the balanced force technique. *International Endodontic Journal* **30**, 386–96.

Blum JY, Cohen A, Machtou P, Micallef JP (1999a) Analysis of forces developed during mechanical preparation of extracted teeth using Profile NiTi rotary instruments. *International Endodontic Journal* **32**, 24–31.

Blum JY, Machtou P, Micallef JP (1999b) Location of contact areas on rotary Profile instruments in relationship to the forces developed during mechanical preparation on extracted teeth. *International Endodontic Journal* **32**, 108–14.

Bryant S, Thompson S, Al-Omari M, Dummer PMH (1998a) Shaping ability of Profile rotary nickel–titanium instruments with ISO sized tips in simulated root canals: Part 1. *International Endodontic Journal* **31**, 275–81.

Bryant S, Thompson S, Al-Omari M, Dummer PMH (1998b) Shaping ability of Profile rotary nickel–titanium instruments with ISO sized tips in simulated root canals: Part 2. *International Endodontic Journal* **31**, 282–9.

Camps JJ, Pertot WJ (1994a) Relationship between file size and stiffness of stainless steel instruments. *Endodontics and Dental Traumatology* **10**, 260–3.

Camps JJ, Pertot WJ (1994b) Torsional properties of stainless steel Canal Master U and Flexogates. *International Endodontic Journal* **27**, 334–8.

Camps J, Pertot WJ (1994c) Torsional and stiffness properties of Canal Master U stainless steel and nitinol instruments. *Journal of Endodontics* **20**, 395–8.

Eggert C, Peters O, Barbakow F (1999) Wear of Nickel–Titanium Lightspeed instruments evaluated by scanning electron microscopy. *Journal of Endodontics* **25**, 494–7.

Gambarini G (2000) Rationale for the use of low-torque endodontic motors in root canal instrumentation. *Endodontics and Dental Traumatology* **16**, 95–100.

Glosson CR, Haller RH, Dove SB, del Rio C (1995) A comparison of root canal preparations using NiTi hand, NiTi engine driven, and K-Flex endodontic instruments. *Journal of Endodontics* **21**, 146–51.

Haikel Y, Serfaty R, Bateman G, Senger B, Allemann C (1999) Dynamic and cyclic fatigue of engine-driven rotary Nickel–Titanium endodontic instruments. *Journal of Endodontics* **25**, 434–40.

International Organization for Standardisation (1992) *Dental Root-Canal Instruments- Part 1: Files, Reamers, Barbed Broaches, Rasps, Paste Carriers, Explorers and Cotton Broaches*. Geneva: ISO.

Luebke NH, Lausten LL, Brantley WA, Mitchell JC (2001) Torsional performance of Nickel-titanium Gates Glidden drills with an applied bending deflection (abstract). *Journal of Dental Research* **80**, 259.

Mandel E, Adib-Yazdi M, Benhamou LM, Lachkar T, Mesgouez C, Sobel M (1999) Rotary Ni-Ti profile systems for preparing curved canals in resin blocks: influence of operator on instrument breakage. *International Endodontic Journal* **32**, 436–43.

Peters OA, Schönenberger K, Laib A (2001a) Effects of four NiTi preparation techniques on root canal geometry assessed by Micro computed tomography. *International Endodontic Journal* **34**, 221–230.

Peters OA, Laib A, Göhring TN, Barbakow F (2001b) Changes in root canal geometry after preparation assessed by high-resolution computed tomography. *Journal of Endodontics* **27**, 1–6.

Pettiette MT, Olutayo Delano E, Trope M (2001) Evaluation of success rate of endodontic treatment performed by students with stainless-steel K-files and Nickel–Titanium hand files. *Journal of Endodontics* **27**, 124–7.

Portenier I, Lutz F, Barbakow F (1998) Preparation of the apical part of the root canal by the Lightspeed and step-back techniques. *International Endodontic Journal* **31**, 103–11.

Pruett J, Clement D, Carnes DJ (1997) Cyclic fatigue testing of nickel–titanium endodontic instruments. *Journal of Endodontics* **23**, 77–85.

Rowan MB, Nicholls JI, Steiner J (1996) Torsional properties of Stainless Steel and Nickel–Titanium endodontic files. *Journal of Endodontics* **22**, 341–5.

Sattapan B, Palamara JEA, Messer HH (2000a) Torque during canal instrumentation using rotary Nickel–Titanium files. *Journal of Endodontics* **26**, 156–60.

Sattapan B, Nervo GJ, Palamara JEA, Messer HH (2000b) Defects in rotary Nickel–Titanium files after clinical use. *Journal of Endodontics* **26**, 161–5.

Schäfer E (2000) Wurzelkanalbehandlungen. *Deutsche Zahnärztliche Zeitschrift* **55**, 730–40.

Schäfer E, Lau R (1999) Comparison of cutting efficiency and instrumentation of curved canals with Nickel–Titanium and stainless-steel instruments. *Journal of Endodontics* **25**, 427–30.

Schneider SW (1971) A comparison of canal preparation in straight and curved root canals. *Oral Surgery* **32**, 271–5.

Schrader C, Ackermann M, Barbakow F (1999) Step-by-step description of a rotary root canal preparation technique. *International Endodontic Journal* **32**, 312–20.

Serene TP, Adams JD, Saxena A (1995) *Nickel–Titanium Instruments: Applications in Endodontics*. St. Louis, MO, USA: Ishiaku EuroAmerica, Inc.

Silvaggio J, Hicks ML (1997) Effect of heat sterilisation on the torsional properties of rotary Nickel–titanium endodontic files. *Journal of Endodontics* **23**, 731–4.

Thompson SA (2000) An overview of nickel–titanium alloys used in dentistry. *International Endodontic Journal* **33**, 297–310.

Thompson SA, Dummer PMH (1997a) Shaping ability of ProFile .04 taper Series 29 rotary nickel–titanium instruments. Part 1. *International Endodontic Journal* **30**, 1–7.

Thompson SA, Dummer PMH (1997b) Shaping ability of

ProFile .04 taper Series 29 rotary nickel–titanium instruments. Part 2. *International Endodontic Journal* **30**, 8–15.

Weine FS (1996) *Endodontic Therapy*, 5th edn. St. Louis, MO, USA: Mosby.

Wu MK, Fan B, Wesselink P (2000) Leakage along apical root fillings in curved root canals. Part I: Effects of apical transportation on seal of root fillings. *Journal of Endodontics* **26**, 210–6.

Yared GM, Bou Dagher FE, Machtou P (1999) Cyclic fatigue of ProFile rotary instruments after simulated clinical use. *International Endodontic Journal* **32**, 115–9.

Yared GM, Bou Dagher FE, Machtou P (2000) Cyclic fatigue of ProFile rotary instruments after clinical use. *International Endodontic Journal* **33**, 204–7.

Zuolo ML, Walton RE (1995) Instrument deterioration with usage: Nickel–Titanium versus stainless steel. *Quintessence International* **28**, 397–402.

